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# THE VARESTRAINT TEST FOR REFRACTORY METALS

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Task II of Contract NAS 3-11827

Paul Moorhead, Project Manager

Astronuclear Laboratory

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FINAL REPORT

# THE VARESTRAINT TEST FOR REFRACTORY METALS

by

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WESTINGHOUSE ASTRONUCLEAR LABORATORY
Pittsburgh, Pennsylvania 15236

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

November, 1970

Task II of Contract NAS 3-11827

Fracture and Hot Crack Resistance of Welds in T-111 and ASTAR-811C

NASA Lewis Research Center
Cleveland, Ohio
Paul E. Moorhead, Project Manager
Materials and Structures Division

Astronuclear Laboratory

# FOREWORD

This program was conducted by the Westinghouse Astronuclear Laboratory under NASA Contract NAS 3-11827. Mr. P. E. Moorhead of the NASA Lewis Research Center, Materials and Structures Division, was the NASA Project Manager for the program.

The objectives delineated and the results reported herein represent the requirements of Task II of Contract NAS 3-11827. Additional investigations which were performed as a part of this program are the subjects of additional reports. The final reports for this contract are the following:

| Task | Title | Report Number |
| --- | --- | --- |
| I | Influence of Restraint and Thermal Exposure on Welds in T-111 and ASTAR-811C | NASA CR-72858 |
| II | The Varestraint Test for Refractory Metals | NASA CR-72828 |
| III | Investigation of High Temperature Fracture of T-111 and ASTAR-811C | NASA CR-72859 |

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## ABSTRACT

The principles of the Varestraint test developed by Savage and Lundin[1] were applied to the evaluation of refractory metal alloys. This required development of a special test apparatus employing a modest specimen size for improved economy and compatible with the high purity inert atmosphere required for welding these alloys[2,3]. Minimum specimen size is desirable because of the high cost of these alloys and also to permit timely testing of limited production developmental alloys. The Varestraint apparatus described in this report satisfies these requirements providing a timely and economic test for hot crack sensitivity. This test can be used both for alloy development and production surveillance. The test apparatus was designed for use in vacuum purged dry boxes and is completely compatible with high purity inert atmosphere. Augmented strain can be varied continuously from 1/4% thru 4%. In addition to varying the augmented strain - the primary Varestraint variable - the effect on hot cracking of varying other weld parameters such as unit weld length heat input have also been studied. Test reproducibility, in terms of bending or strain rate, was demonstrated using high speed photography.

Alloys evaluated in demonstrating this apparatus included the columbium-base alloys FS-85, B-66, and SCb-291, and the tantalum alloys Ta-10W, T-111, T-222, and ASTAR-811C. All of these are commercially available except ASTAR-811C (Ta-8W-1Re-0.7Hf-0.025C) which is an advanced alloy scaled up to production for the first time in this program. Primary emphasis was directed toward the tantalum-base alloys T-111 and ASTAR-811C due to their current importance for space power system applications requiring a combination of excellent weldability, ductility, and high temperature strength. B-66 is a particularly useful alloy for demonstrating the flexibility and range of this apparatus in defining hot crack sensitivity as a function of Varestraint test parameters. The propensity this alloy exhibits for hot cracking has been explained in terms of an empirically-derived correlation based on the relationship of Mo-V-Zr contents. In contrast to B-66 the other alloys are relatively insensitive to compositional variations or weld parameter selections. Excellent correlation was achieved using this test.

## 1.0 INTRODUCTION

This report describes the application of the Varestraint Test to the evaluation of hot crack propensity in refractory metal alloys. This test was developed by Savage and Lundin[1] and has been applied by others in the evaluation of more conventional materials. For testing refractory metal alloys, constraints peculiar to these materials had to be satisfied as described in this report.

The Varestraint Test provides a means of intentionally augmenting shrinkage strain during welding as a means of screening materials for hot crack sensitivity. Although hot cracking is associated with shrinkage strain, in practice shrinkage is not readily measured or calculated because it is a complex function of weld parameters and weldment configuration. Hence, independent control of weld strain during welding is an attractive approach in testing for hot crack sensitivity. Conversely, because of the complexity of the weld strains, use of the Varestraint data is ultimately dependent on correlation with field welding results.

Varestraint testing is accomplished by bending a test specimen during welding to achieve a given strain across the weld. This strain is determined by selection of the radius of curvature of the bending die. This is shown schematically in Figure 1. Bending is initiated immediately prior to the time the welding electrode is at the point of tangency of the specimen and die block. Each level of augmented strain requires an individual test specimen. Bead-on-plate GTA welds are normally employed in this test.

This test has several intrinsic advantages over other methods of hot crack testing.

- The specimen configuration is simple and inexpensive to prepare and the test is inexpensive to run.
- The test is performed while welding just as shrinkage strains occur during welding.
- An infinite variety of weld thermal cycles and gradients are screened simultaneously. Hence, screening is achieved with minimal testing compared with other hot ductility test methods.
- The augmented strain can be varied independently of the other test variables.

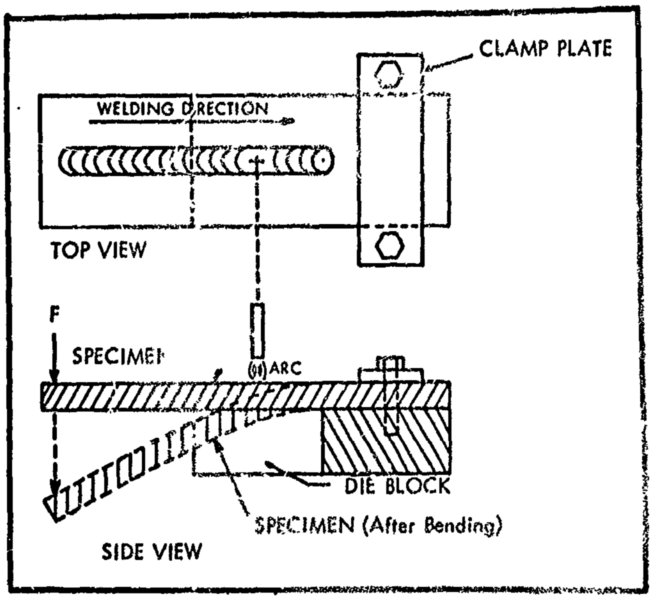


FIGURE 1 - Schematic: Bending Technique for Augmenting Strain by Varestraint Testing [1].

For these reasons, this test is even more attractive for exotic or developmental alloys such as refractory metal alloys. These are usually quite expensive . Hence , a maximum amount of information must be obtained during testing with minimal material consumption. Further, since these are usually of very limited production, it is essential that quality standards be developed independent of exhaustive field testing. Finally, since hot cracking tendencies are sensitive to a wide spectrum of variables such as contamination, a discriminating hot cracking test is very attractive as a quality assurance screening technique.

We have designed the Varestraint test described in this report specifically for refractory metal alloys. The major design features accommodated were:

- Modest specimen size due to the extreme cost of refractory metal alloys. Experimental heats may cost several hundred dollars per pound. A,1 x 6 x 1/8 inch specimen size was selected.
- All sources of weld atmosphere contamination were avoided. The unit operates in a vacuum purged weld chamber of highest quality. The structural materials must not outgas, and the potential leaks in the pneumatic drive system required positive sealing.
- All sources of metallic contamination were eliminated. Holding fixtures and die blocks were made from molybdenum for this purpose.
- The test unit was designed as compactly as possible to permit maximum flexibility in testing. The unit is portable. It provides an unobstructed view of the specimen and full accessibility from one side so that specimens can be changed in glove box operations.
- The specimen was located so as to permit electron beam welding as well as GTA welding. Only GTA welding has been employed to date.
- The stroke linkage was designed to maintain simple bending throughout the stroke or to intentionally augment bending with a proportionate tensile component should this become necessary to achieve conformance to the bending die.

All of these objectives were successfully achieved. Qualification of this unit consisted of the following:

- Operation in a monitored inert gas dry box without compromising the quality of the weld chamber atmosphere.
- Proof of discrimination by evaluating refractory metal alloys with differing field welding records.
- Proof of reliability by testing numerous samples in one test run without breaking the weld chamber to air.
- Proof of reproducibility by utilizing high speed photography to measure consistency of bending rates for various dies.

## 2.0 TECHNICAL PROGRAM

### 2.1 Program Materials

The alloys evaluated in the course of this investigation are listed in Table 1 with their nominal chemical compositions. Actual chemical analyses supplied by the vendors for the various alloys are presented in Table 2. Check analyses were performed for the interstitial elements C, O, and N because of their pronounced influence on alloy properties, and, hence, as a quality assurance measure.

All materials were tested as 0.125 inch thick sheet in the fully recrystallized condition. Refractory metal alloys are nearly always used in the recrystallized condition due to the obvious advantages offered in terms of long time thermal stability.

The overall weldability and elevated temperature stability of these alloys has been the subject of a recently-concluded NASA-sponsored research program[4]. In terms of overall weldability these alloys may be "ranked" from easiest to most difficult as:

1. Ta-10W, SCb-291
2. FS-85
3. T-111, T-222, ASTAR-811C (being evaluated in a current program)
4. B-66

| Alloy | Nominal Composition (w/o) |
|---|---|
| T - 111 | Ta - 8W - 2Hf |
| ASTAR-811C | Ta - 8W - 1Re - 0.7Hf - 0.025C |
| FS - 85 | Cb - 27Ta - 10W - 1Zr |
| T - 222 | Ta - 9.6W - 2.4Hf - 0.01C |
| Ta - 10W | Ta - 10W |
| B - 66 | Cb - 5Mo - 5V - 1Zr |
| SCb - 291 | Cb - 10W - 10Ta |

TABLE 1 - Alloys Evaluated in Varestraint Testing Program.

TABLE 2 - Vendor and Check Analyses of Program Alloys [a]

| Alloy | Certified Analyses (Avg.) | | | | | | | | | | | Check Chemistry | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ta | Cb | W | Hf | Mo | Re | V | Zr | C | $O_2$ | $N_2$ | C | $O_2$ | $N_2$ |
| T-111 | Bal. | | 8.2 | 2.0 | | | | | 40 | 80 | 12 | 33 | 40 | 12 |
| ASTAR-811C | | | | | | | | | | | | | | |
| Ht. 650056 | Bal. | | 8.1 | 0.9 | | 1.17 | | | 240 | 60 | 20 | - | - | - |
| Ht. 650078 | Bal. | | 8.1 | 0.9 | | 1.40 | | | 300 | 70 | 10 | 210 | 5 | 5 |
| FS-85 | 28.1 | Bal. | 10.6 | | | | | 0.94 | 20 | 90 | 60 | 32 | 53 | 47 |
| T-222 | Bal. | | 9.2 | 2.55 | | | | | 115 | 50 | 20 | 119 | 17 | 11 |
| B-66 | | Bal. | | | 5.17 | | 4.89 | 1.00 | 95 | 110 | 63 | 37 | 120 | 70 |
| Ta-10W | Bal. | | 9.9 | | | | | | 50 | 40 | 20 | 5 | 10 | 10 |
| SCb-291 | 9.83 | Bal. | 10.0 | | | | | | 20 | 110 | 40 | 22 | 101 | 20 |

(a) Metallic analyses in weight percent. Interstitial analyses in ppm (weight).

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The above ranking is of course subject to the conditions that all welding be done in an ultra-high quality inert welding atmosphere. This requirement is not unique for the program alloys but is general for all refractory metal alloys. This ranking does not imply any particular difficulty exists in welding these alloys but rather that some alloys tend to be more sensitive to weld parameter variations than others. In fact, hot cracking has only been observed in one of these alloys, B-66, and then only when the (Mo + V)/Zr ratio is allowed to exceed 10.2[5].

## 2.2 Apparatus Design

The Varestraint test apparatus designed and built for testing refractory metal alloys is shown in Figure 2. The apparatus is shown in the post test (specimen bent) position. It incorporates the following features:

- All stainless steel construction except for specimen clamps and die block which are molybdenum.
- A double sealed pneumatic drive. The pneumatic cylinder is sealed within a stainless can. The plunger is sealed with a welded bellows and the can utilizes a static O-ring flange seal.
- The plunger is equipped with an adjustable stop so that specimens are not bent over the end of the radius blocks.
- The stroke arm is mounted to a pivot arm which serves the purpose of maintaining simple bending throughout the stroke. An alternate connection is provided for the stroke arm on the pivot arm to augment bending with tensile stress if required.
- Triggering occurs at the specimen so that the entire stroke mechanism can be preloaded. This was done to achieve minimum delay in triggering and maximum reproducibility. Before firing the trigger rests against the trigger release. It is shown locked in the released position.
- During welding the thoriated tungsten electrode traverses the test specimen from right to left. The bare electrode is mounted in a molybdenum chill block of sufficient mass to provide cooling of the electrode during the short run time.
- Rolling element bearings are used at all pivot points to minimize stroke resistance. Linear bearings are used on the electrode traverse mechanism.

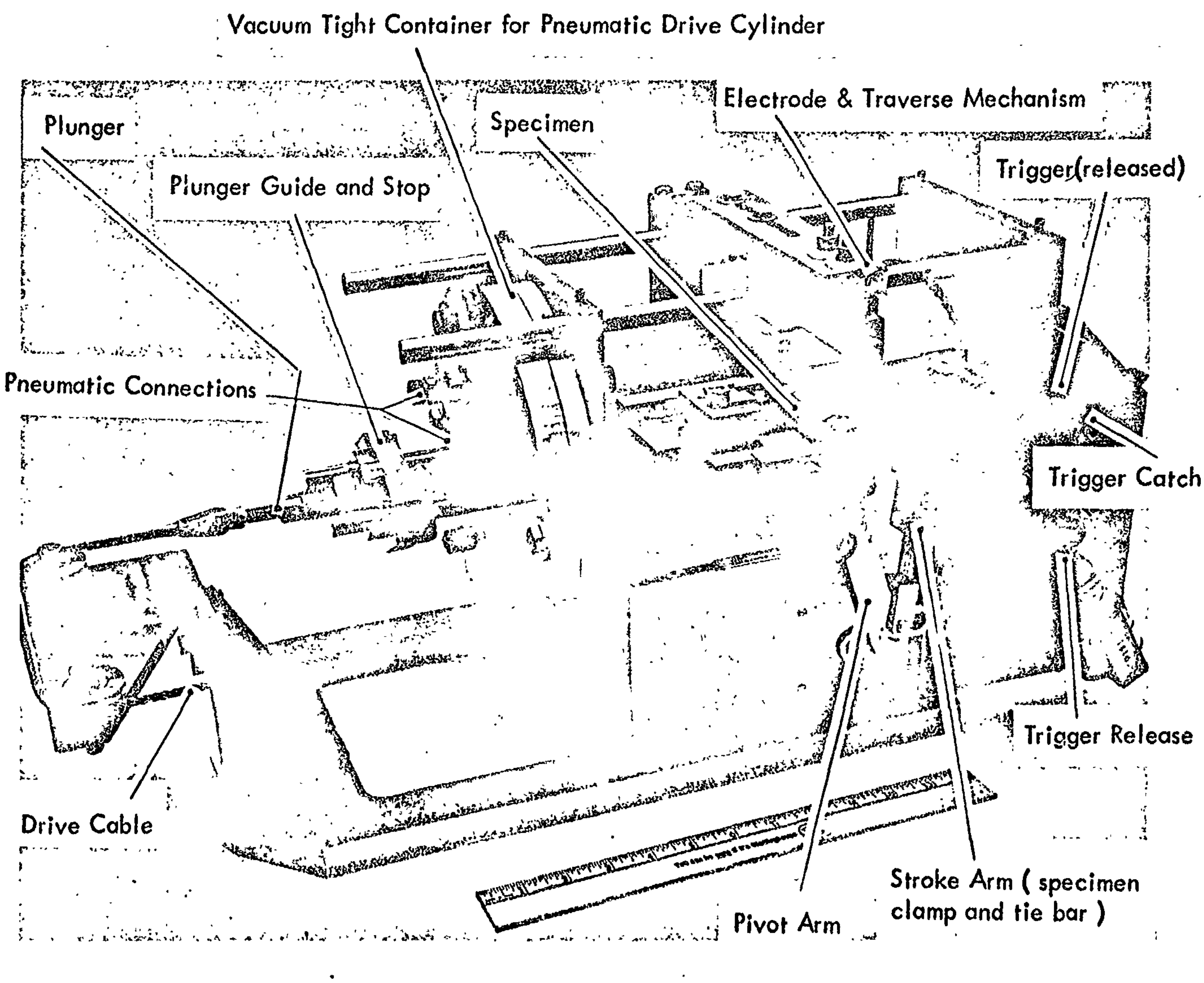



FIGURE 2 - Varestraint Test Apparatus for Refractory Metals

- In the final configuration of this unit the electrode traverse mechanism was mounted independently to eliminate shock transmission and consequent electrode vibration during firing.

- Flexible stainless steel convoluted gas lines (not shown) are attached to the pneumatic connections for charging the cylinder. Helium or argon is used for this purpose.

- The stroke mechanism is activated automatically by means of a microswitch attached to the drive mechanism ( not shown ) .

### 2.3 Testing Procedure

Test specimens 0.125 inch x 1 inch wide x 6 inches long are loaded cantilever fashion into the testing fixture with two 0.125 inch x 0.5 inch wide x 6 inches long molybdenum "bending bars." The bending bars are located approximately 0.5 inches apart on each side of, and parallel to, the longitudinal dimension of the specimen. The use of bending bars prevents kinking or preferential bending of the specimen and guarantees conformance of the specimen to the die block. The actual test is accomplished by the sudden application of the bending load as the gas tungsten-arc welding electrode approaches the point of tangency between the curved surface of the die block and the cantilevered specimen. The arc is allowed to travel an additional 3/4 to 1 inch before being extinguished.

The magnitude of the augmented strain to which the specimen is subjected at the instant of bending is:

augmented (tangential) strain = $t/2R$

where $t$ = specimen thickness, and
$R$ = radius of curvature of the block

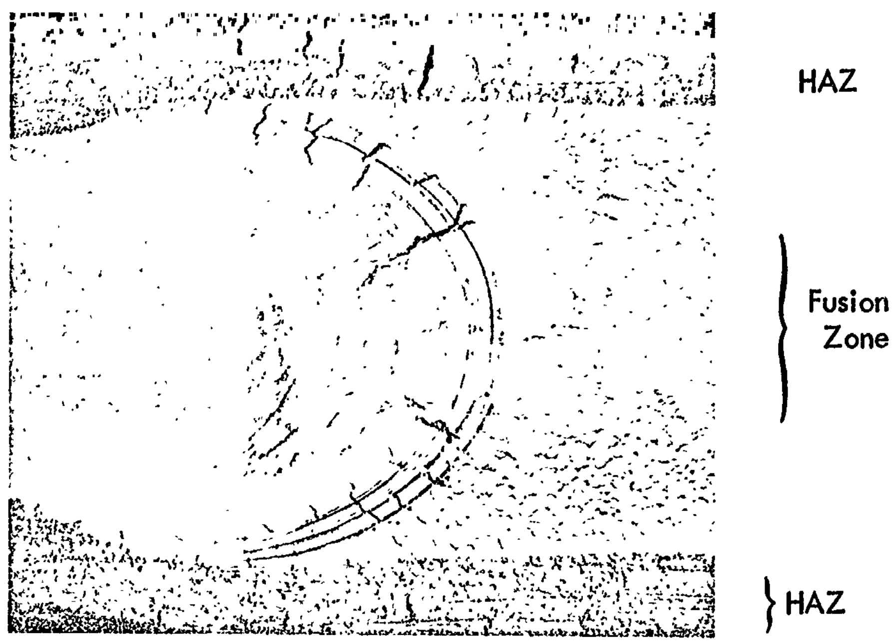
Hence, by varying the radius of curvature of the die block one can vary the augmented strain. For this program die blocks were machined out of arc cast molybdenum having radii of curvature so as to allow testing of 0.125 inch thick specimens at augmented strain levels of 1/4, 1/2, 3/4, 1, 2, 3, and 4%. Since the magnitude of the augmented strain is not a function of the welding parameters, the effects of welding process, alloy composition, and other parameters which influence the metallurgical features of the weld can be separately evaluated from those due to externally imposed mechanical restraint.

For the purposes of this program and in order not to introduce too great a number of variables, welding parameters were selected which would give a reproducible weld width and weld puddle geometry. The bulk of the GTA welding was done at 15 ipm, a weld speed found to be practical for virtually all refractory metal alloys[4]. Where the number of specimens permitted, tests were conducted at additional welding speeds. Specific weld parameters used for the various alloys are provided later in the Discussion section of this report.

Following testing, the as-welded specimens are examined for cracks using a low power bench microscope. The total combined crack length in the weld fusion zone is used as the index for hot cracking sensitivity of the weld metal[1]. The total crack length is determined by means of a calibrated reticule located in the eyepiece of a metallurgical microscope. In general, crack counting was performed directly on the as-tested specimen surface although for purposes of comparison several specimens were examined after approximately 0.01 inches had been removed from the as-tested surface by polishing and etching. The crack length values resulting from the two inspection techniques varied little, so long as the amount of material removed was not excessive. In general, only those specimens intended to be examined in more detail metallographically were polished and etched.

As-tested and lightly polished and etched photographs of the same areas of an ASTAR-811C specimen are shown in Figure 3. Cracking in the weld zone and in the heat-affected zone (HAZ) are readily seen following testing at 4% augmented strain during GTA welding at 15 ipm.

A typical plot of total crack length in the weld fusion zone vs. augmented strain level is shown in Figure 4 (for B-66). Figure 4 also shows the effect of varying weld parameters (i.e the weld speed - hence the heat input/unit weld length). The effect seen for B-66 of more severe cracking at higher welding speeds was observed for all metals and is discussed later in this report.




AS TESTED 15X

← Welding Direction

LIGHTLY POLISHED AND ETCHED 15X

FIGURE 3 - ASTAR-811C Specimen after Varestraint Testing.

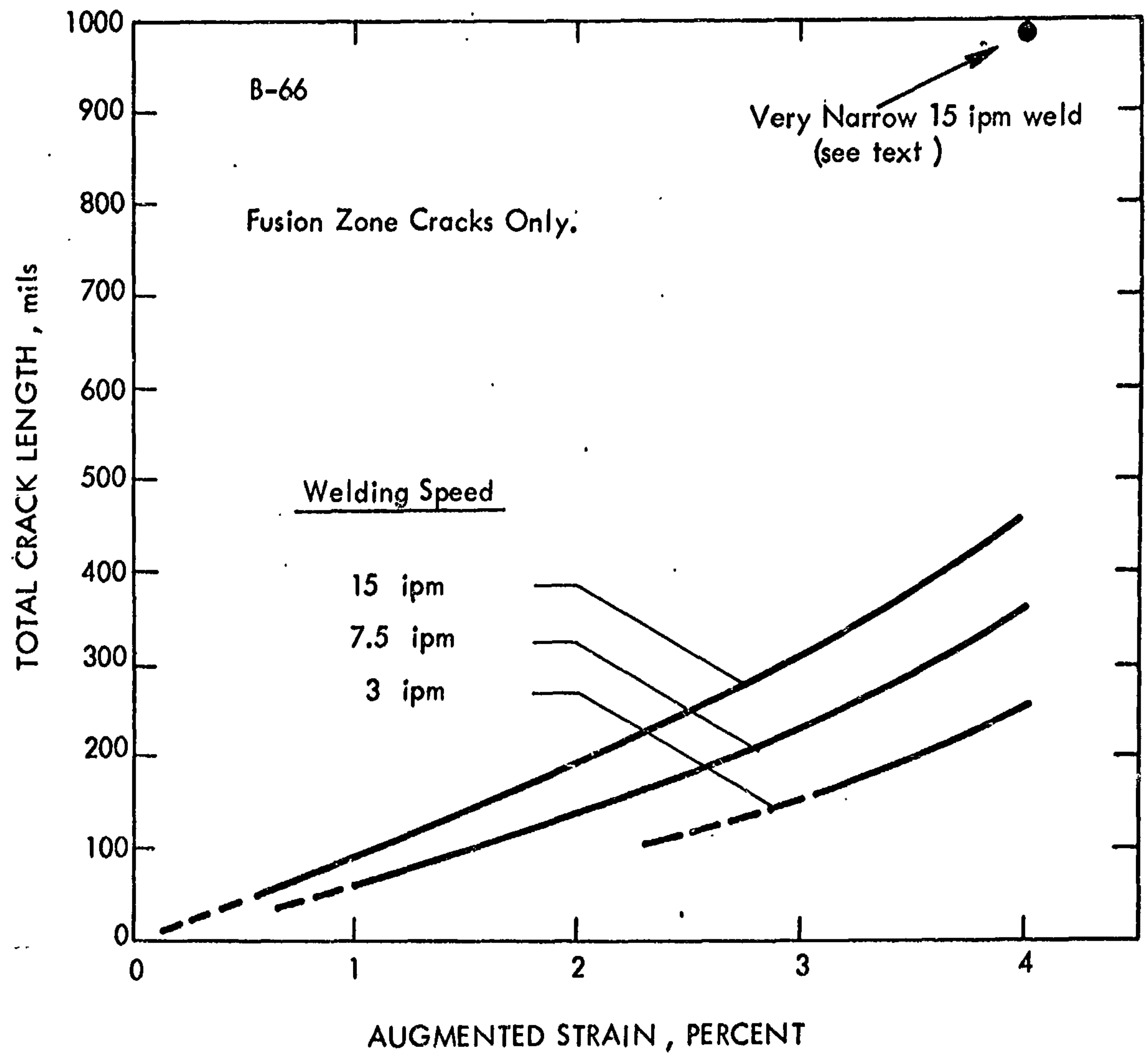



FIGURE 4 - Total Crack Length vs. Augmented Strain for B-66 Alloy Varestraint Test Specimens.

## 2.4 Apparatus Qualification

The Varestraint test apparatus was qualified for this program by determining:

- Its effect on weld atmosphere quality.
- Its performance in correlating test results with field experience for several refractory metal alloys.
- The reproducibility of results as discussed in a later section of this report, and
- The actual bending rate using high speed photography.

Excellent results were achieved in all the qualification tests conducted. Use of the apparatus in a high purity helium atmosphere produced no detrimental effects. After six hours of exposure, during which time four tests were made, a helium sample contained the following impurities.

| Element or Compound | ppm (Volume) |
|---|---|
| $N_2$ | 5.18 |
| $O_2$ | 1.03 |
| Ar | 0.11 |
| $CO_2$ | 0.43 |
| $CH_4$ | 0.06 |
| $C_2H_6$ | 0.14 |
| $C_3$, $C_4$ hydrocarbons | 0.10 |
| $C_5$, $C_7$ hydrocarbons | 0.09 |
| Ne | 5.94 |
| $H_2O$ | <1.0 |

Less than 8 ppm total active impurities were present after six hours operation demonstrating that the test apparatus had no detrimental effect on the welding atmosphere[2].

Several alloys were chosen specifically to assess the ability of the Varestraint test to discriminate between alloys of known hot crack sensitivity. Results were in excellent agreement with practice. These are summarized in Figure 5. The alloy sensitivity is in full agreement with observed behavior[3] as discussed later under Results.

Results of high speed photography of the operation of this apparatus are summarized in Figures 6, 7, and 8. Figures 6 and 7 depict the effect of using different bend radii while Figure 8 shows the effect of lowered firing pressure. All three figures correlate bend angle and time with location on the test specimen relative to bend initiation. Approximately the first 3/4 inch from the start of the bend is relevant in this test. Hence, the substandard pressure resulted in stretch-out of the stroke by a factor of approximately five. For these tests steel bending bars were used with aluminum specimens to simulate the hot refractory metal specimens and molybdenum bending bars used in the actual tests. The photographic data was accumulated using a camera speed of 4500 frames/second. The photographic evaluation revealed entirely satisfactory operation of the Varestraint tester with the tester providing a very fast, nearly instantaneous bend. The photographic results were used to calculate the approximate strain rate by the method shown in Figure 9. As seen in that figure, to simplify the analysis the deformation is taken to occur in a "plastic hinge" region having a width approximately equal to the specimen thickness. The strain rate calculated in this manner is $10^3$ min$^{-1}$. This high strain rate, per se, did not seem to affect the results and there did not seem to be any extraneous effects on the ranking of the alloys tested.

## 3.0 RESULTS AND DISCUSSION

### 3.1 Screening and Performance Evaluation Tests

Preliminary tests were performed on the alloys B-66, Ta-10W, SCb-291, FS-85, and T-222. The purposes of these tests were several. First, by using a series of alloys having well-defined general welding characteristics we were able to assess the ability of the Varestraint test apparatus to discriminate between them. In addition, whereas most of the experimental data available regarding the welding characteristics of these alloys has been accrued using specimens of such size and geometry that little mechanical restraint exists, the Varestraint test is capable of imposing an exact, known longitudinal strain on the outer surface of the weld specimen. Hence,

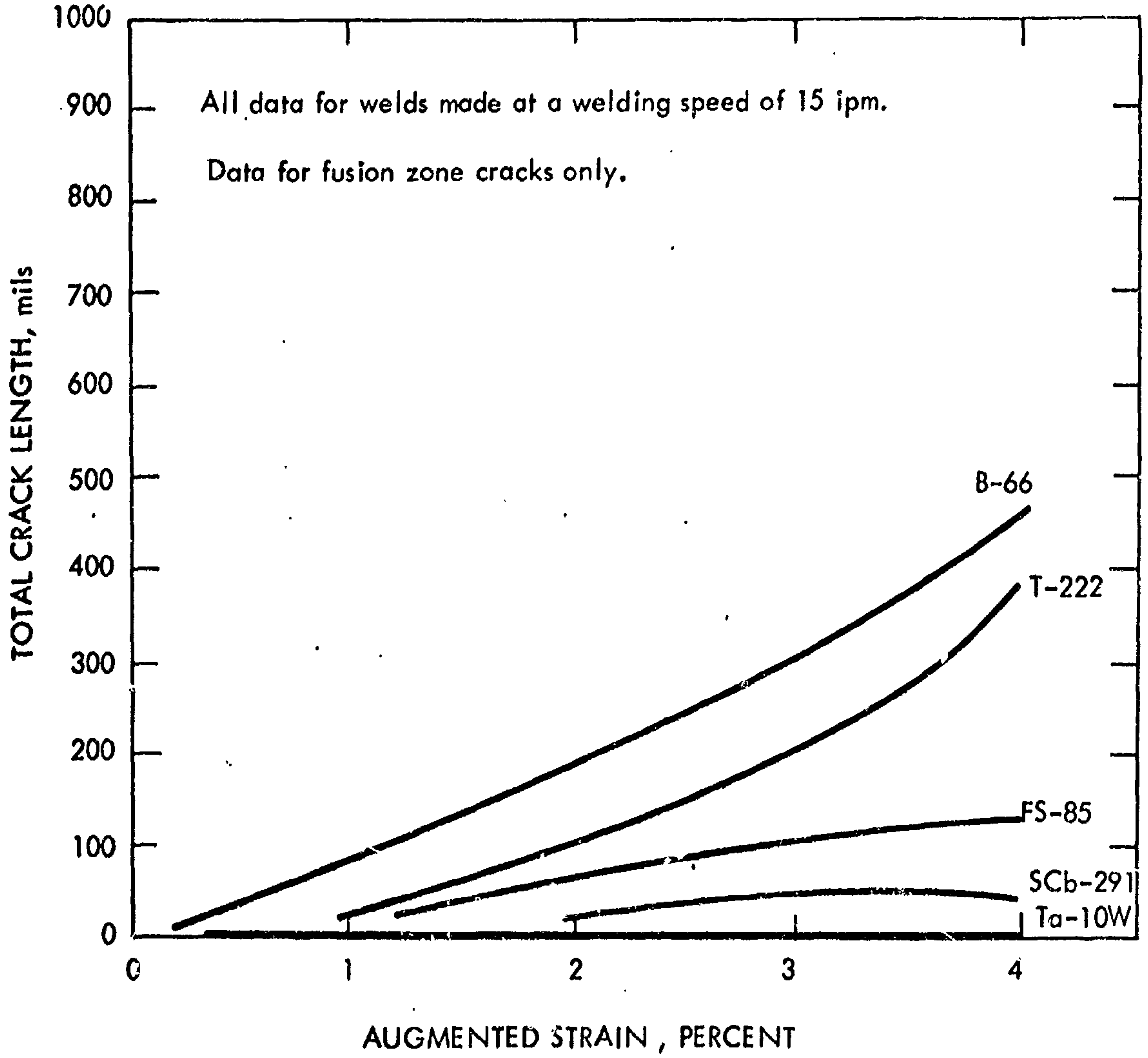



FIGURE 5 - Comparison of Total Crack Length vs. Augmented Strain for Several Refractory Metal Alloys.

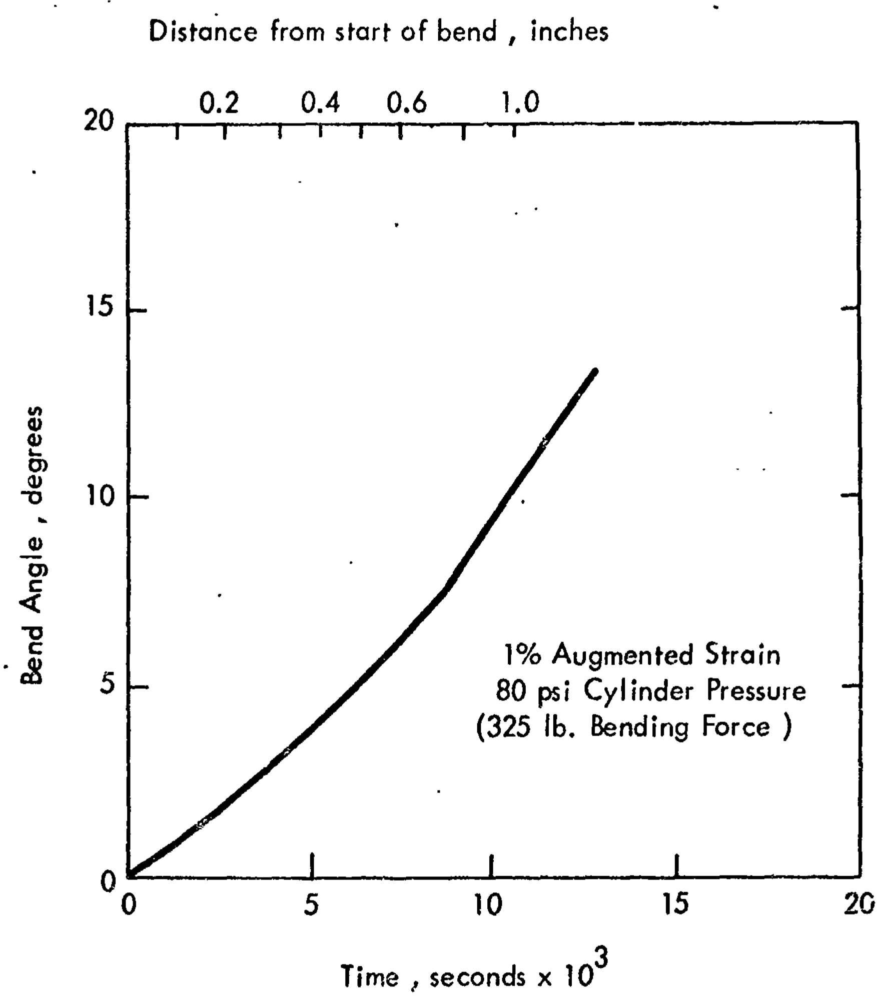



FIGURE 6 - Bend Angle vs. Time for 1% Augmented Strain.

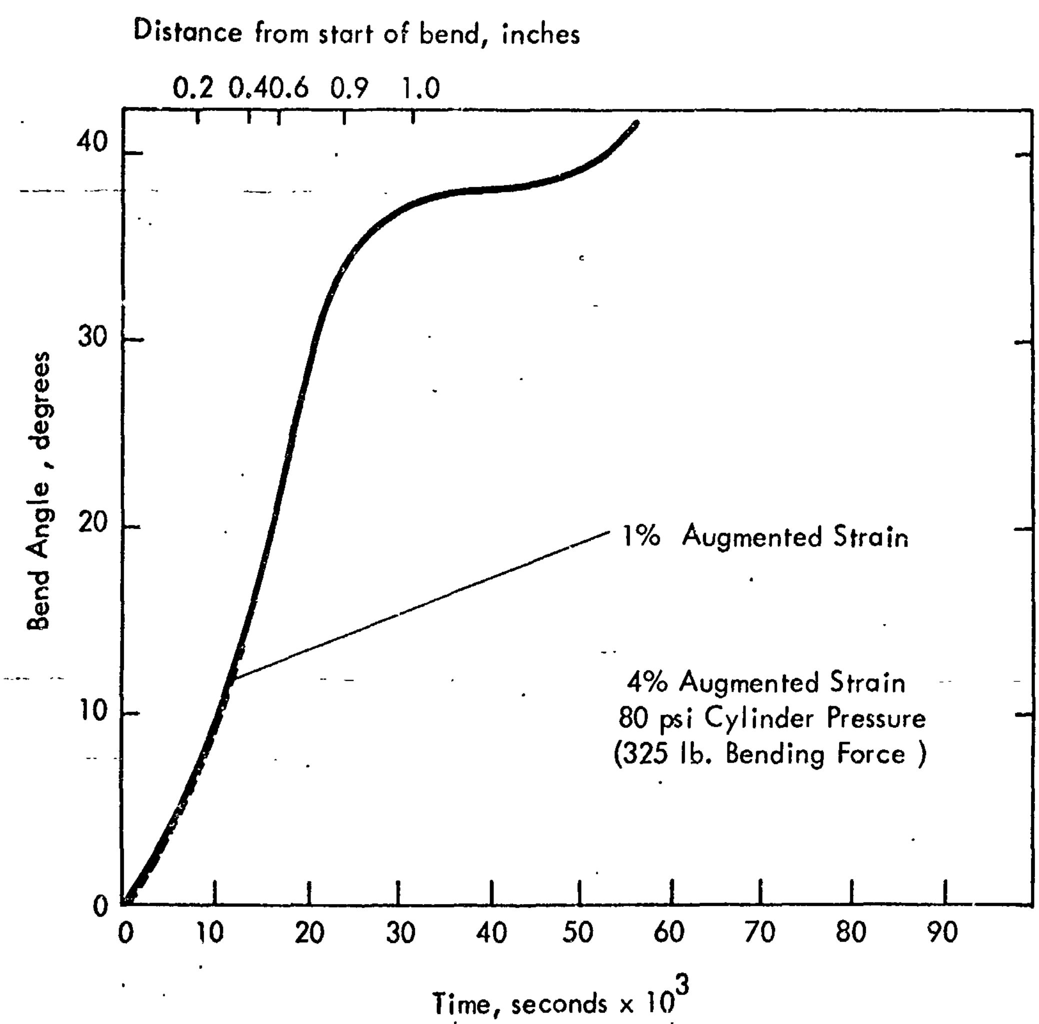



FIGURE 7 - Bend Angle vs. Time for 4% Augmented Strain.

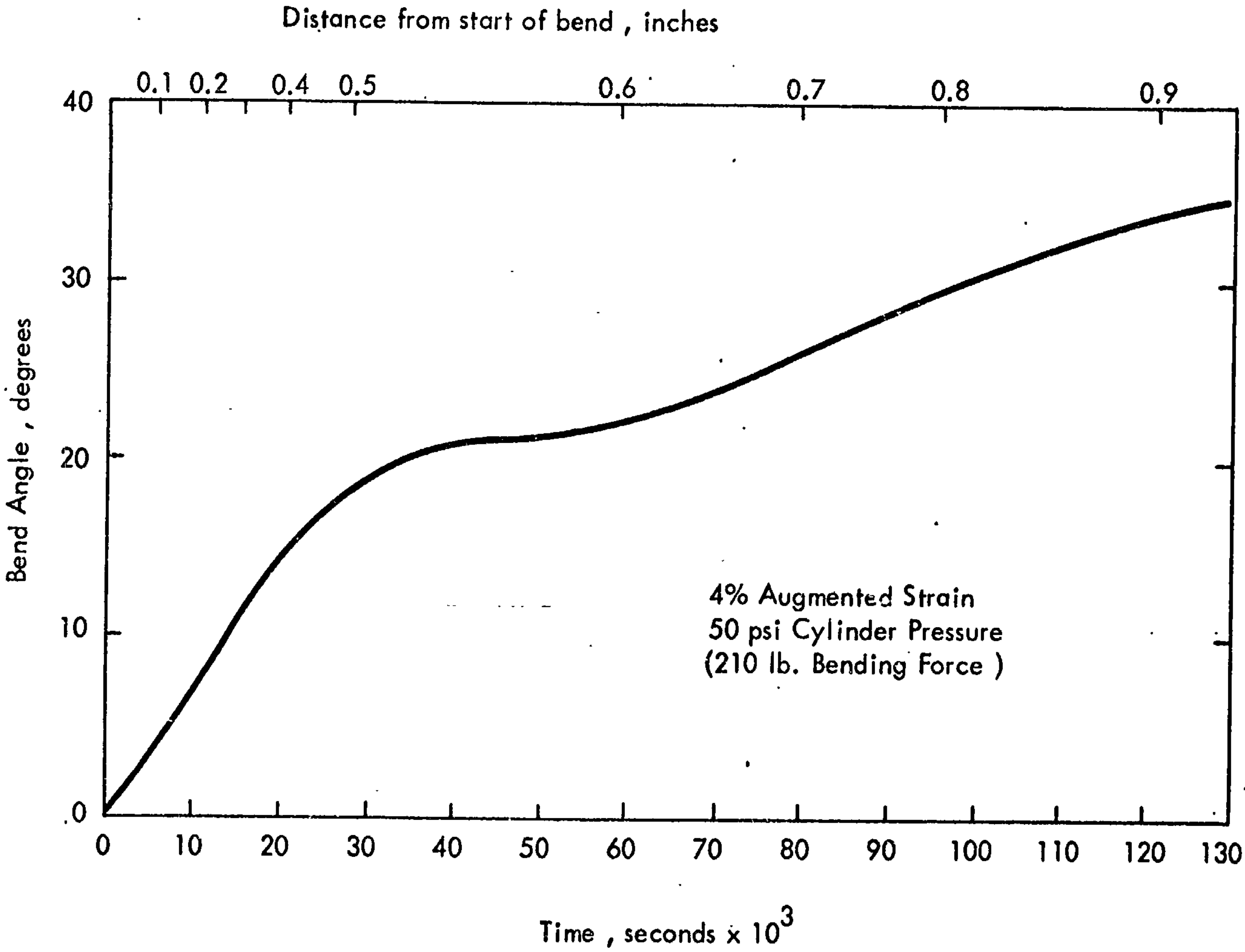
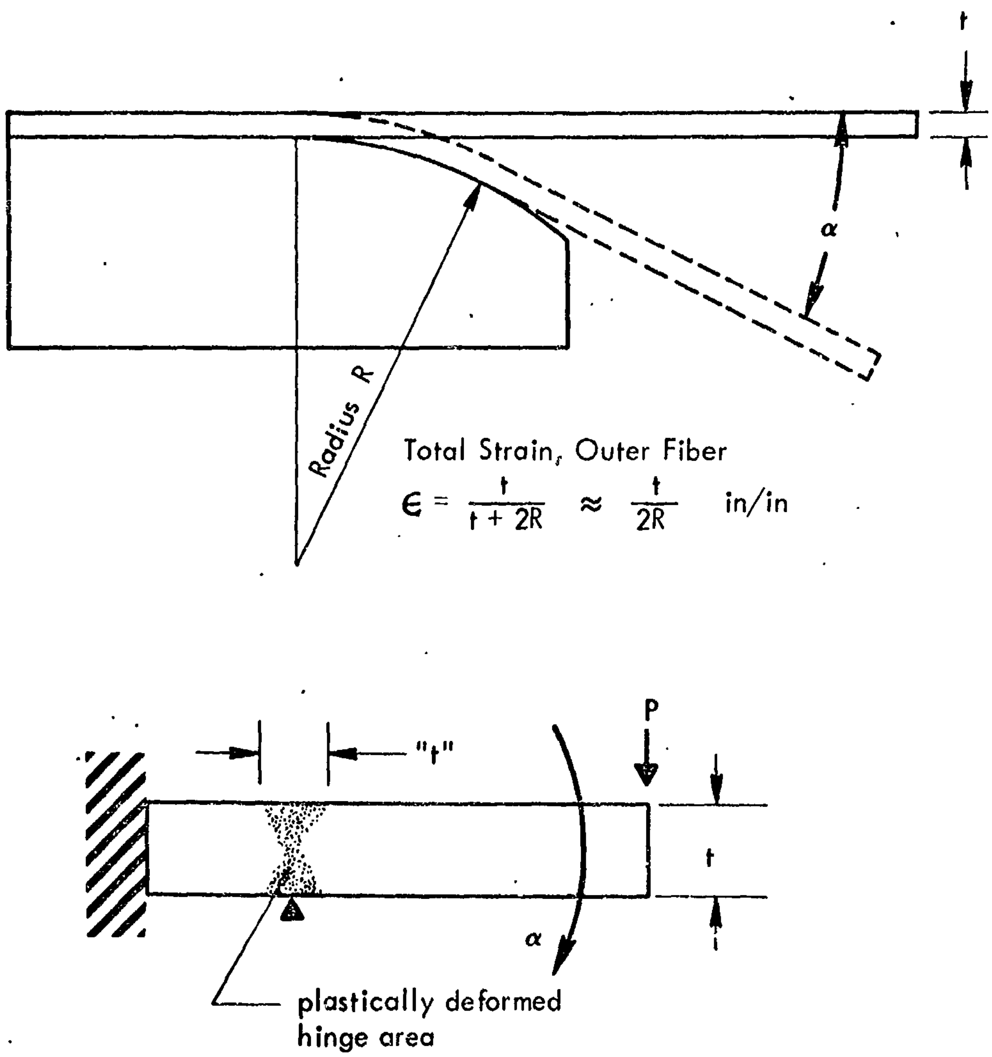



FIGURE 8 - Bend Angle vs. Time for 4% Augmented Strain with 60% Bending Force.




"t" ≈ t = assumed effective length of plastic hinge

$\omega$ = angular velocity of bending (slope of $\alpha$ vs. time curve)

Approximate Strain Rate

$$\boxed{\dot{\epsilon} \approx \frac{1/2\, t\omega}{\text{"t"}} \approx \frac{1}{2}\omega}$$

FIGURE 9 - Schematic Showing Analysis of Varestraint Test Used to Calculate the Approximate Strain Rate.

the information obtained is specific regarding the ability of each of these alloys to accommodate various levels of strain during welding.

The results of all preliminary tests have already been presented in Figure 5. All of the data represented in Figure 5 are for tests made on welds produced at 15 ipm. The weld currents used in each case were as follows:

| Alloy | Weld Current (amps) |
|---|---|
| T-222 | 210 |
| FS-85 | 180 |
| Ta-10W | 220 |
| SCb-291 | 180 |
| B-66 | 180 |

The total crack length is plotted as a function of augmented strain for each of the alloys used in the screening tests. The hot cracking sensitivity reflected the exact order of weldability established previously, ranging from Ta-10W which did not exhibit hot cracking at even the most severe test conditions to B-66 which contained hot cracks at every condition evaluated. All alloys except Ta-10W displayed a measurable degree of hot crack sensitivity. The hot cracking tendency displayed by B-66 correlates well with the observed behavior of this alloy. Field welding of T-222 and FS-85 has shown these to be sensitive to underbead cracking in multipass plate welds but not sensitive to classic hot cracking. Hence, this test may provide an indication of sensitivity to failure modes other than classic hot cracking.

In addition to total crack length a useful index of cracking sensitivity is provided by the "cracking threshold". This represents the minimum level of augmented strain required to produce cracking for a given set of weld parameters. For the alloys represented in Figure 5 the cracking threshold values, for a weld speed of 15 ipm, were :

| Alloy | Cracking Threshold |
|---|---|
| B-66 | <1/2% |
| T-222 | ~ 1% |
| FS-85 | ~ 1% |
| SCb-291 | 2% |
| Ta-10W | >4% |

Although most tests were made using a weld speed of 15 ipm the limited number of tests made at other welding speeds indicates the metallurgical factors which influence hot cracking are somewhat tempered by reducing the welding speed. This was seen for the B-66 test results in Figure 4.

During the preliminary testing it was found desirable to maintain a nearly constant weld width in the specimens of a given alloy. The inadvertent use of too low a weld current resulted in testing a very narrow weld in one of the B-66 specimens. This is the data point in Figure 4 which is seen to be exceptionally high relative to similarly tested wider welds. The narrow weld forces a relatively small total volume of solidifying weld metal to accommodate a considerable amount of strain. Interaction between the mechanical effects due to changing soecimen/weld geometries and metallurgical effects arising from changes in heat input and freezing rate are analytically very complex. Fortunately, test results to data indicate that small variations in weld width can be tolerated. Hence, this variable is readily accommodated.

In summary, performance of this unit proved to be excellent in all respects. The cracking index developed accounts well for classic hot cracking which occurs at temperatures in the vicinity of the effective solidus of the alloy as the weldment cools. In addition, there is evidence the test may also provide information regarding hot ductility limitations of both the base metal and weld metal. The latter evidence is obtained by noting the occurrence and severity of heat affected zone cracking. HAZ cracking was observed in many of the specimens tested but detailed analysis of this phenomenon was beyond the scope of the present study. Where duplicate tests were conducted the variation in test results was less than 15%, indicating excellent reproducibility.

### 3.2 T-111 and ASTAR-811C

Primary emphasis in the testing program was directed toward the tantalum-base alloys T-111 and ASTAR-811C due to their current importance for space power system applications requiring a combination of excellent weldability, ductility, and high temperature strength.

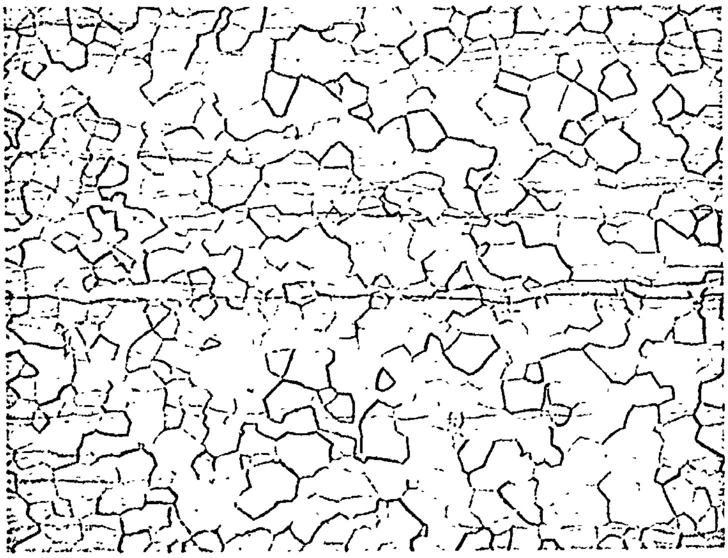
All T-111 and ASTAR-811C material used in this program was tested as fully recrystallized 1/8 inch thick plate. Figures 10 and 11 show the pre-test microstructure of the T-111 and ASTAR-811C evaluated, respectively. Both heats of ASTAR-811C are represented on that Figure.

The test results for T-111 and ASTAR-811C are presented in tabular form in Tables 3 and 4, respectively, and plotted in Figures 12 and 13, respectively, as a function of total crack length in the weld fusion zone vs. augmented strain. The correlation appears to be excellent for all conditions evaluated. The previously noted effect of weld width was taken into consideration during the testing of T-111 and ASTAR-811C. An effort was made to select weld parameters which would produce a uniform weld width - approximately 0.165 to 0.180 inches. For the data of Figures 12 and 13 this necessitated use of the following weld currents vs. welding speed (the same weld currents were used for both alloys);

| Welding Speed | Weld Current |
|---|---|
| 30 ipm | 260 amps. |
| 15 | 210 |
| 7.5 | 180 |
| 3 | 140 |

It should be noted that the resulting welds were somewhat narrower than those used for the preliminary alloy testing; hence, the conditions of testing were probably a little more severe for T-111 and ASTAR-811C. Individual data points are not shown on Figures 12 and 13. However, in order to evaluate test reproducibility several duplicate tests were conducted at the most severe conditions evaluated (4% augmented strain - 15 ipm welding speed). The resulting scatter in the data was found to be no greater than 10%.

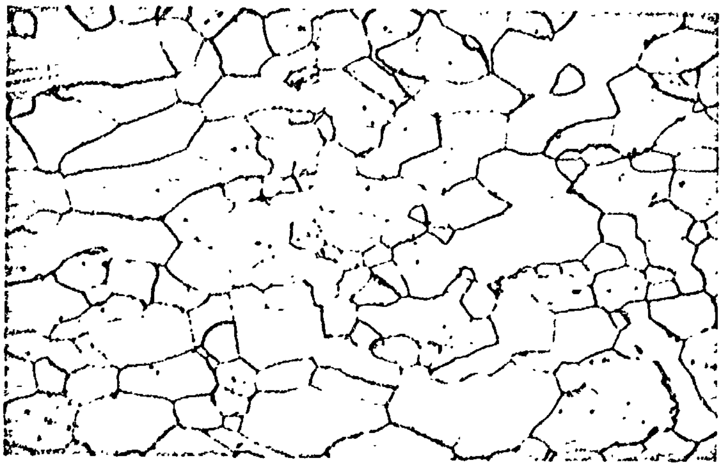
The data plotted in Figure 13 for ASTAR-811C represents tests on two different heats of this alloy. The performance of the low rhenium Heat 650056 is seen to be considerably better than that of the high rhenium Heat 650078. At the time of the purchase of ASTAR-811C for this program the specification for rhenium was 1.00 to 1.50 weight percent. Since that time, the



23,075 100X

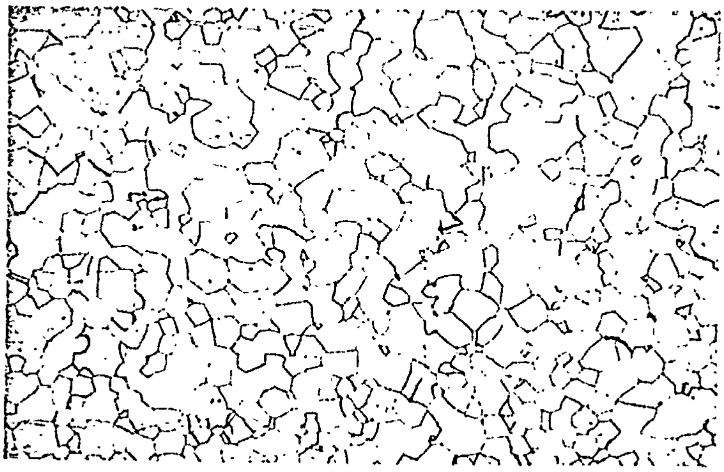
Avg. Grain Size
34.8 μm
ASTM 6.5

FIGURE 10 - Pre-test Microstructure of T-111.



23,074 Heat 650078 400X

Avg. Grain Size
11.4 μm
ASTM 10



23,073 Heat 650056 100X

Avg. Grain Size

26 μm
ASTM 7.5

FIGURE 11 - Pre-test Microstructure of ASTAR-811C.

TABLE 3 - Varestraint Data for T-111

| Specimen Number | Percent Strain | Weld Conditions | | Results | | |
|---|---|---|---|---|---|---|
| | | Speed (ipm) | Current (amps.) | No. of Cracks | Max. Crack Lgth. (mils) | Total Crack Lgth. (mils) |
| 1 | 4 | 15 | 210 | 17 | 7 | 105 |
| 2 | 4 | 7.5 | 190 | 17 | 5 | 60 |
| 3 | 1 | 15 | 210 | - | - | - |
| 4 | 3 | 15 | 210 | 30 | 6 | 100 |
| 5 | 2 | 15 | 210 | 9 | 5 | 40 |
| 6 | 3 | 7.5 | 180 | 26 | 8 | 70 |
| 7 | 2 | 7.5 | 180 | - | - | - |
| 8 | 4 | 3 | 140 | 21 | 6 | 65 |
| 9 | 3 | 3 | 140 | 19 | 5 | 50 |
| 10 | 3 | 15 | 210 | 18 | 14 | 80 |
| 11 | 4 | 15 | 210 | 30 | 8 | 115 |
| 12 | 4 | 15 | 245 | 38 | 18 | 180 |
| 13 | 4 | 7.5 | 180 | 31 | 7 | 110 |
| 14 | 4 | 30 | 260 | 23 | 48 | 220 |

TABLE 4 - Varestraint Data for ASTAR-811C

| Specimen Number | Percent Strain | Weld Conditions | | Results | | |
|---|---|---|---|---|---|---|
| | | Speed (ipm) | Current (amps.) | No. of Cracks | Max. Crack Lgth. (mils) | Total Crack Lgth. (mils) |
| 1 | 4 | 15 | 210 | 39 | 9 | 140 |
| 2 | 4 | 7.5 | 210 | 29 | 9 | 110 |
| 3 | 1 | 15 | 210 | - | - | - |
| 4 | 3 | 15 | 210 | 30 | 8 | 120 |
| 5 | 2 | 15 | 210 | 18 | 4 | 45 |
| 6 | 4 | 7.5 | 180 | 25 | 10 | 115 |
| 7 | 2 | 7.5 | 180 | 6 | 3 | 20 |
| 8 | 4 | 3 | 140 | 32 | 8 | 90 |
| 9 | 3 | 3 | 140 | 18 | 5 | 55 |
| 10 | 4 | 15 | 210 | 40 | 12 | 160 |
| 11 | > 4 | 15 | 210 | 38 | 32 | 240 |
| 12 | 4 | 15 | 245 | 50 | 26 | 165 |
| 13 | 4 | 7.5 | 180 | 28 | 9 | 135 |
| 14 | 4 | 30 | 260 | 30 | 43 | 195 |
| 15 | 4 | 15 | 210 | 6 | 10 | 34 |
| 16 | 2 | 15 | 210 | - | - | - |
| 17 | 1 | 15 | 210 | 4 | 4 | 12 |
| 18 | 3 | 15 | 210 | 9 | 6 | 40 |
| 19 | 3 | 7.5 | 180 | 8 | 3 | 16 |
| 20 | 4 | 7.5 | 180 | 10 | 6 | 38 |

Specimens 1 through 14 were from Heat 650078
Specimens 15 through 20 were from Heat 650056

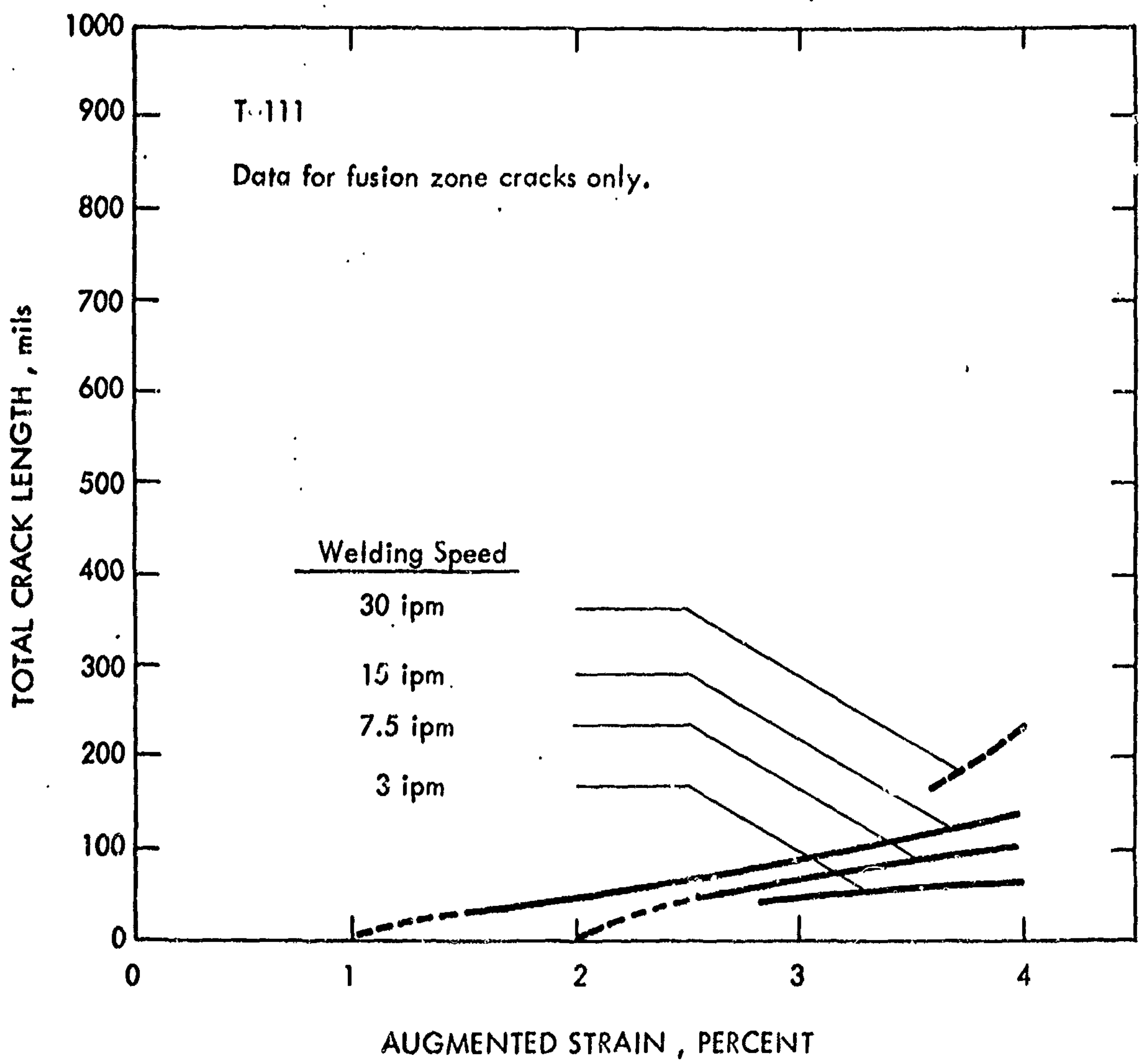



FIGURE 12 - Total Crack Length vs. Augmented Strain for T-111 Alloy Varestraint Test Specimens .

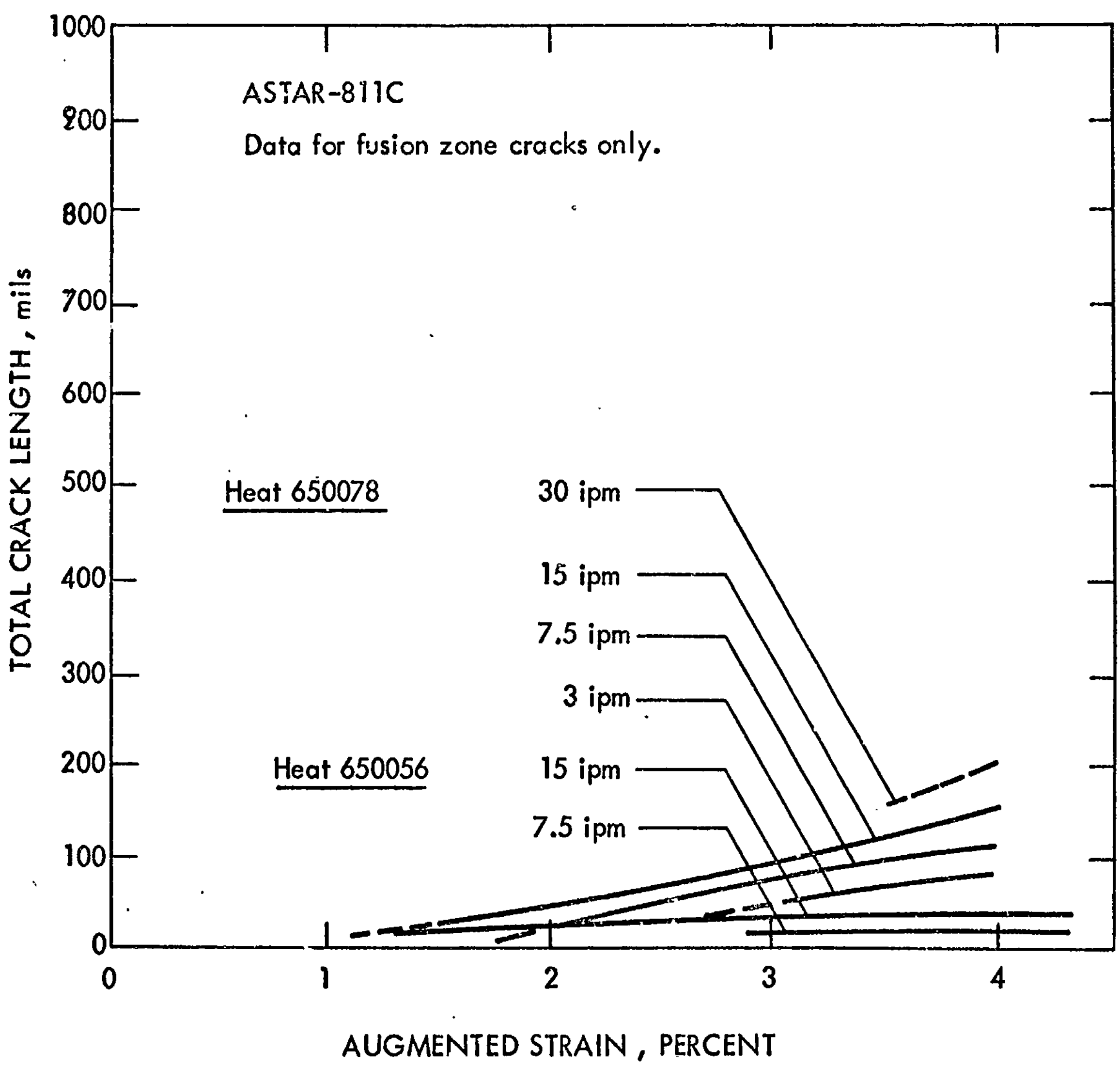



FIGURE 13 - Total Crack Length vs. Augmented Strain for ASTAR-811C Alloy Varestraint Test Specimens.

integration of experience factors accrued in the processing and mechanical testing of ASTAR-811C has resulted in the lowering of the rhenium specification to the range 0.80 to 1.20 weight percent. Hence, the Heat 650078 test data represented on Figure 13 should be viewed as being for "out-of-spec" material and are provided for comparison and for the sake of completeness. Significantly, the Varestraint test was able to discriminate between these two heats of ASTAR-811C despite the rather minor variations in composition.

Figure 14 shows the fusion zone cracking in a T-111 specimen following testing at a 4% augmented strain level. This is not a typical specimen but rather represents the worst incidence of cracking observed in T-111 tested during 15 ipm GTA welding. The hot cracks in the fusion zone are invariably located at the trailing edge of the weld puddle and are seen to lie perpendicular to the location of the solid-liquid interface at the instant of straining. Included in Figure 14 is a 400X photograph of the region around a typical fusion zone hot crack. The slightly different orientations of the various subgrains around the crack confirm the fact hot cracking propagates along solure-enriched grain and subgrain boundaries. A similarly tested (high rhenium) ASTAR-811C specimen is shown in Figure 15. (A high rhenium specimen was used merely because of the scarcity of cracks in the low rhenium specimens). Again, the dominant sites for hot cracks are the subgrain boundaries.

Comparison of Figures 12 and 13 indicates that ASTAR-811C is less prone to hot cracking than is T-111. Although the cracking threshold for both T-111 and ASTAR-811C is in the vicinity of 1% augmented strain, at the strain levels greater than 2% the superiority of ASTAR-811C is evident. This is in agreement with the general behavior observed in multipass GTA plate welding where ASTAR-811C consistently displays a lesser tendency toward underbead grain boundary cracking than T-111.

HAZ cracking was not observed in either T-111 or the low rhenium Heat 650056 ASTAR-811C. The behavior of the high rhenium Heat 650078 ASTAR-811C was erratic in this respect, however, displaying severe HAZ cracking in some specimens and none at all in others. Neither the occur-

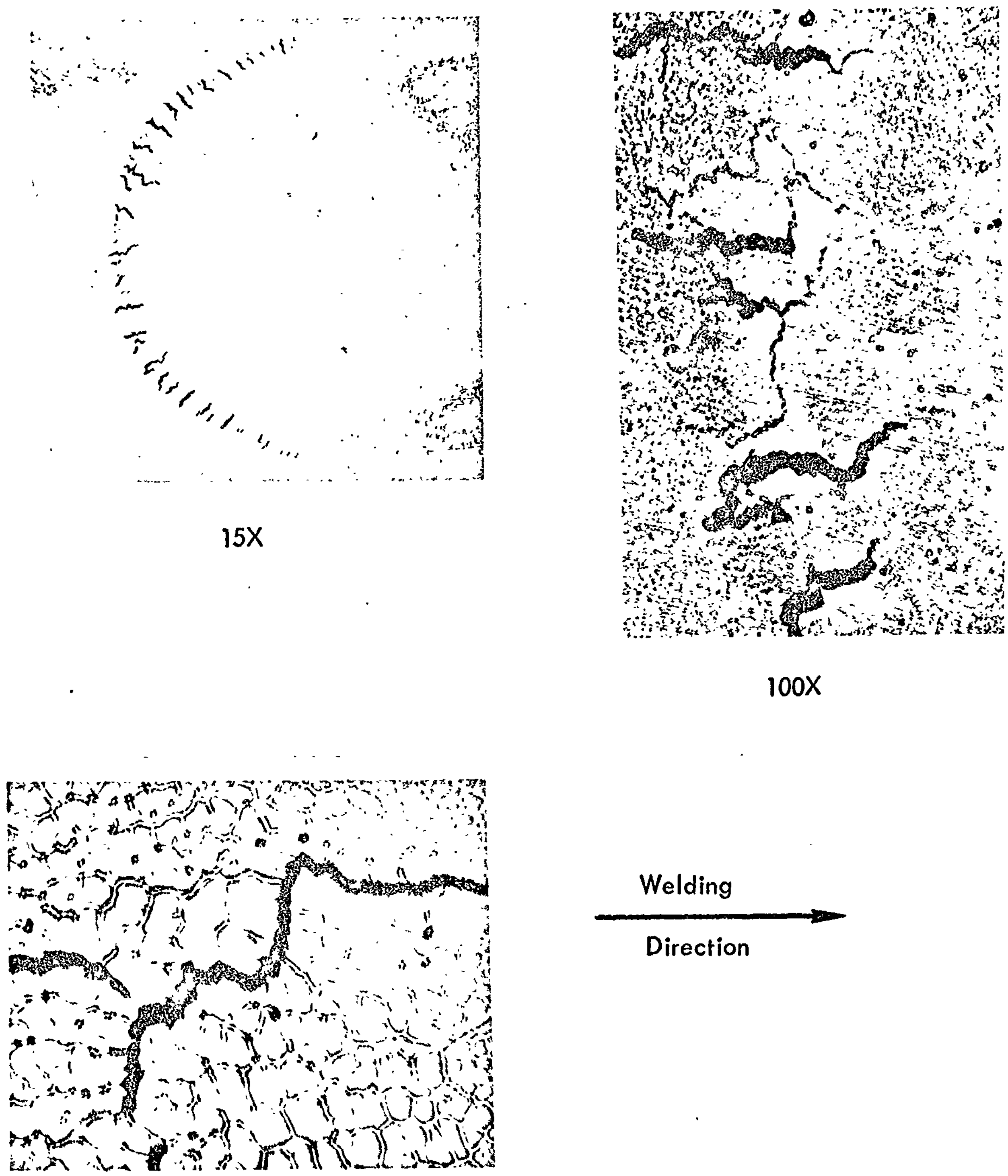
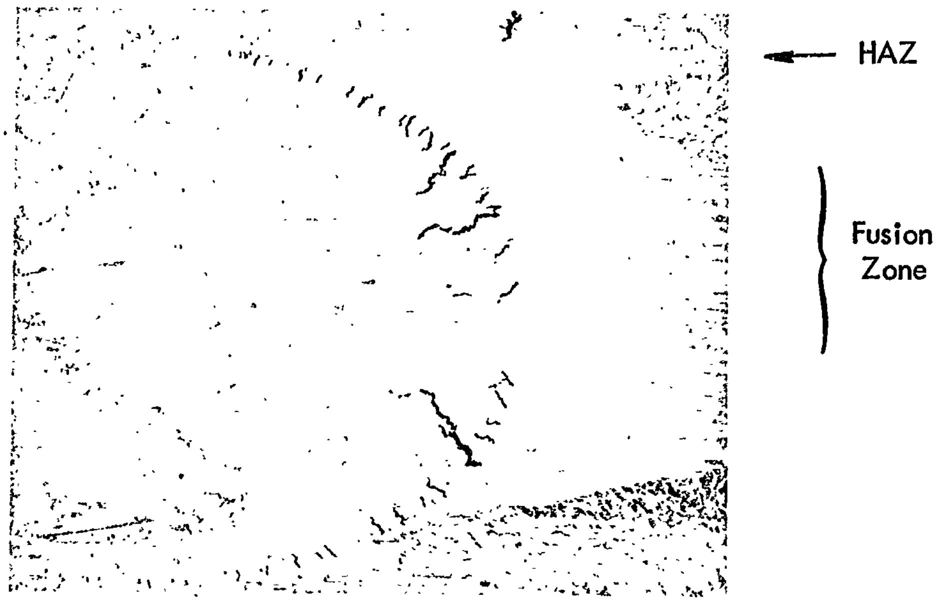
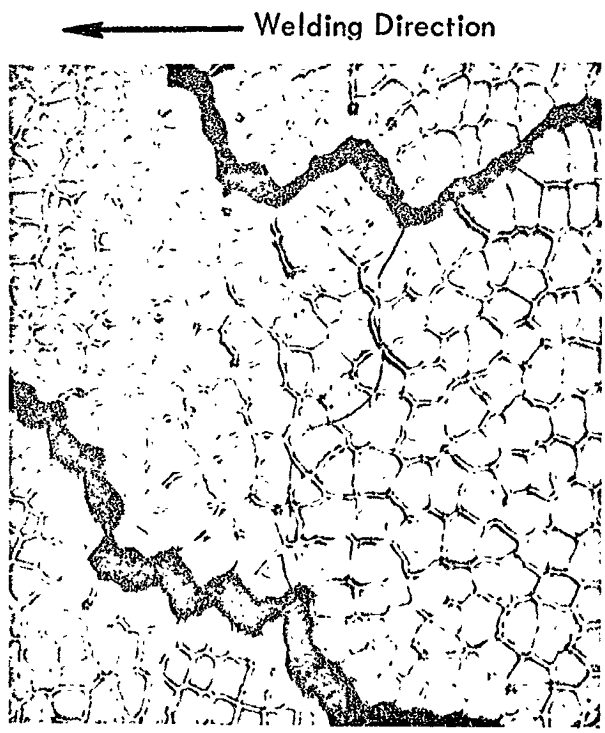



FIGURE 14 - Fusion Zone Hot Cracks in T-111 Specimen Tested at 4% Augmented Strain. Specimen Lightly Polished and Etched Prior to Examination .




15X




400X

FIGURE 15 - Fusion Zone Hot Cracks in ASTAR-811C Specimen Tested at 4% Augmented Strain. Specimen Lightly Polished and Etched Prior to Examination.

rence nor the severity of the HAZ cracking showed a definite relationship to % augmented strain during testing. The ASTAR-811C specimen shown in Figure 3 displays extensive HAZ cracking while in Figure 15 a single HAZ crack is seen. In addition to the more typical cracks of Figure 3 numerous instances were found which looked more like "pits". In most cases these appeared to have likely been the result of weld "splatter" but this general conclusion did not adequately account for all instances where this was seen. A microprobe scan of one of these regions indicated hafnium enrichment and tungsten depletion showing that there was some local inhomogeneity in this material.

To provide a final perspective all of the test results on welds produced at 15 ipm are shown in Figure 16 for all seven refractory metal alloys evaluated. Only the test results for the low rhenium Heat 650056 ASTAR-811C are included in this figure, for those reasons presented previously.

The correlation between these results and the known weld variability of these alloys (see prior "ranking" list ) is excellent. The T-222 data appears slightly higher than might be anticipated but it does fall in the expected order. The higher hafnium content of T-222 relative to T-111 might reasonably be expected to lower the effective solidus temperature in regions of micro-segregation (as in welds) thereby enhancing the possibility of hot cracking. A similar argument might be offered (i.e. higher hafnium content) for the observed difference between T-111 and ASTAR-811C.

## 4.0 CONCLUSIONS

1. The Varestraint test concept of applying augmented strain to a bead-on-plate GTA weld has been modified and adapted to provide a means of evaluating hot cracking sensitivity in the refractory metal alloys. Augmented strain levels from 1/4% through 4% are possible.

2. The Varestraint test capability has been developed without compromise of the stringent environmental controls required for high reliability welds in refractory metal alloys.

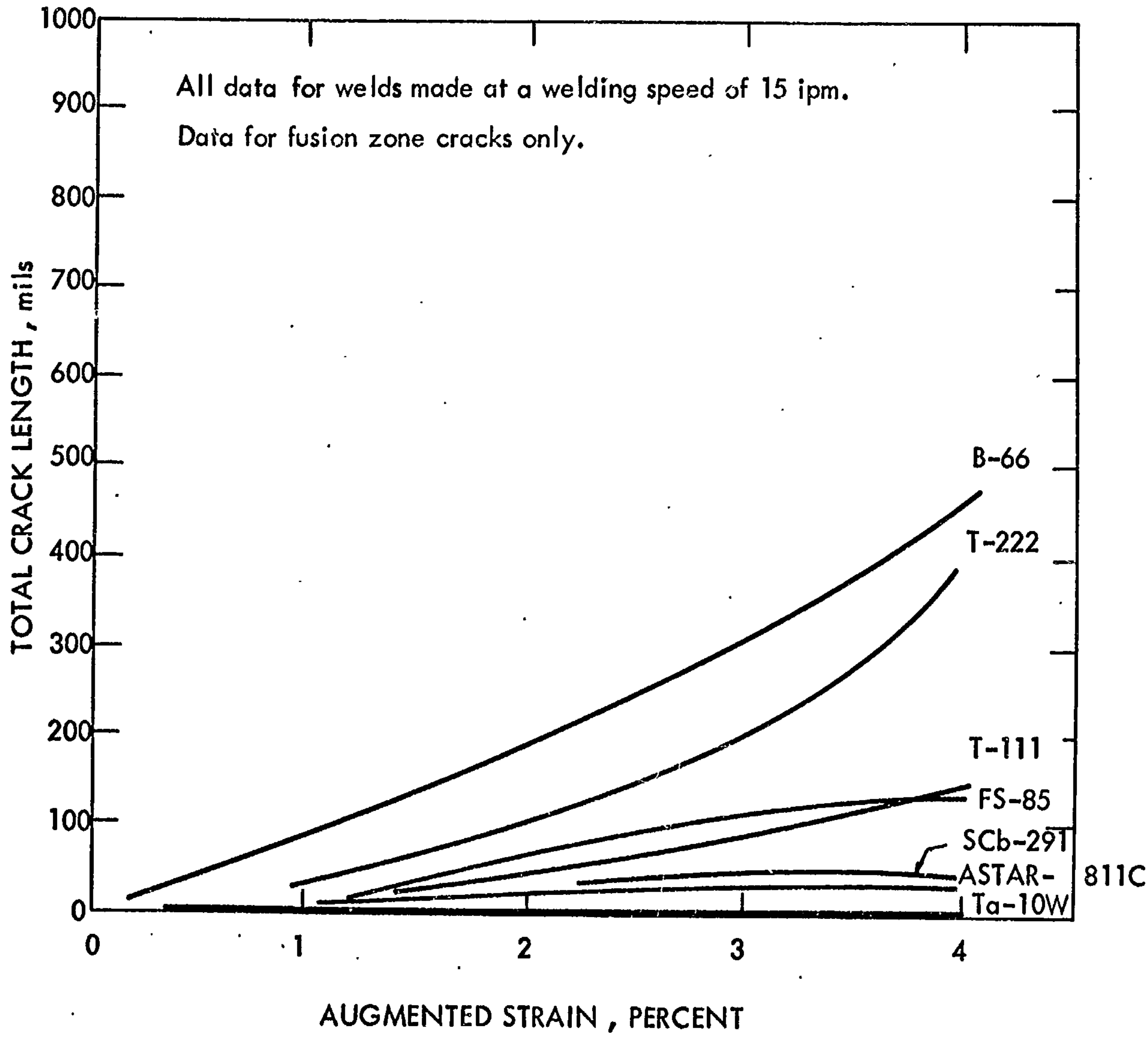



FIGURE 16 - Comparison of Total Crack Length vs. Augmented Strain for All Refractory Metal Alloys Evaluated This Program.

These procedures should be logically applicable to studies on the reactive metals (Zr, Hf, Ti ) and their alloys.

3. Excellent correlation was achieved between test results and previously observed weld quality variability.

4. Refractory metal alloys, with the exception of B-66 and possibly T-222, are not prone to hot cracking.

5. Hot cracking in refractory metal alloys is related to microsegregation in the welds, being invariably located along fusion zone grain and sub ain boundaries.

6. The environmental control capability developed should be of particular value in evaluating the effects of atmospheric contaminants on the weldability of both conventional and developmental materials.

7. Within the somewhat limited framework of the present investigation test reproducibility appears excellent.

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Special recognition is given Mr. A. R. Keeton who reduced our general requirements for the Varestraint test to practice by designing a first class, functional and reliable apparatus.

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